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# HST Observations of High-Density Globular Clusters†

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In this paper we present preliminary results from our HST project aimed at exploring the connection between stellar dynamics and stellar evolution in the cores of high-density globular clusters.

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## 1. Introduction

Until a few years ago Galactic globular clusters (GC) were regarded as ideal laboratories for testing stellar evolution theories and for studying stellar dynamics in *simple* stellar systems, and as important relics of the formation of the Galaxy. For many years most of the research proceeded as if the problems in the single fields mentioned above could be understood and solved independently of each other.

Now, however, each branch of GC studies is realizing that further progress depends on viewing each cluster as a kind of *ecosystem* of interrelated species. We have a growing body of observational evidence that dynamical interactions among stars in high-density clusters can modify their stellar content. Color gradients have been observed from the ground in the central regions of some post-core-collapse (PCC) or high-concentration clusters (*cf.* Djorgovski & Piotto 1993 for a review and references). The gradients are always in the sense of a bluer center, and extend even to the far-UV wavelengths. The gradients reflect radial changes in the stellar population. In addition, Fusi Pecci, Ferraro, & Cacciari (1993) have shown that the length of the horizontal branch (HB), and the presence and the extent of blue tails in particular, are correlated with the cluster density and concentration, in the sense of more concentrated or denser clusters having bluer and longer HB morphologies. The theoretical understanding of these phenomena remains unclear, though it is very likely that binaries and stellar interactions are involved in modifying stars located on the evolved branches of the color-magnitude diagram (CMD).

The exceptional resolving power of HST is of fundamental importance in this kind of study, as it allows observing faint stars in the center, down to the main sequence.

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As an example, in Figure 1 we compare one of the best ground-based images on which our previous investigation (Djorgovski & Piotto 1993) was based with the corresponding HST frame.

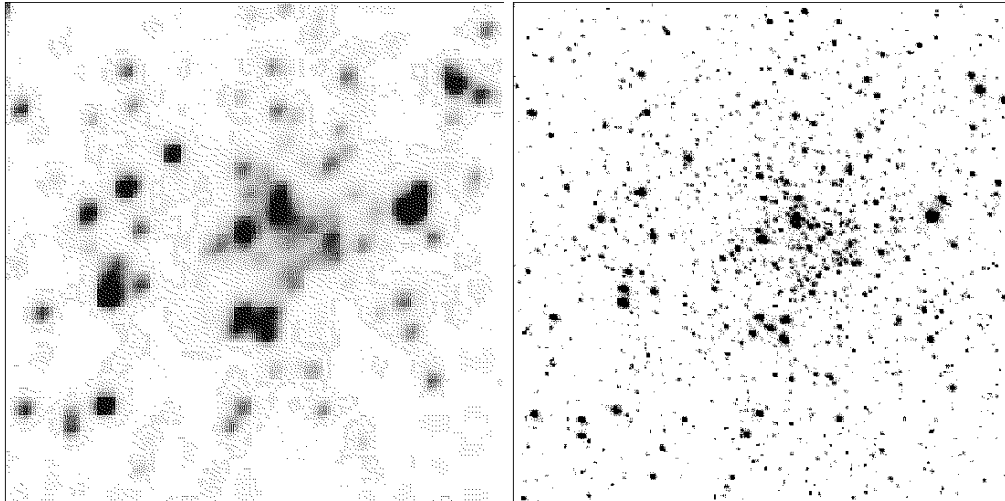


Figure 1. The *left panel* shows a ground-based  $V$ -band image of the inner  $21 \times 21 \text{ arcsec}^2$  of the GC M30, taken at the ESO NTT telescope (seeing  $\text{FWHM} = 0.6 \text{ arcsec}$ ). The *right panel* shows the same field from the PC frame of the WFPC2 camera in the F555W band.

In this paper we present some preliminary results from our HST project specifically devised to explore the connection between stellar dynamics and stellar evolution by investigating the GC star population in the very inner regions of 10 high-density clusters.

## 2. Observations and data reduction

The central regions of 10 GCs were observed with the WFPC2 camera on HST in the F218W, F439W, and F555W bands, during Cycle 6. The targets were chosen on the basis of either their high density and/or concentration or because of the strong UV flux of unknown origin detected by IUE. In our analysis, we used also the archive data (from an HST program by Yanny *et al.*) on 3 additional PCC clusters: NGC 6624, NGC 7078, and NGC 7099. Our cluster sample spans a factor of 100 in metallicity, covering almost the entire GC metallicity range. In this paper we focus on the F439W and F555W images.

The stellar photometry has been obtained with DAOPHOT, setting the parameters as discussed in Cool & King (1995). The F439W and F555W instrumental magnitudes have been transformed into standard  $B$  and  $V$  magnitudes following Holtzman *et al.* (1995). There is a general agreement in the photometric zero point with the previous ground-based investigations, with the noticeable exception of NGC 2808, which seems  $\sim 0.1 \text{ mag}$  fainter in  $V$  and redder than in Ferraro *et al.* (1990).

## 3. The color-magnitude diagrams

The CMDs for the 13 clusters are shown in the following paper by Sosin *et al.*.

From a minimum of  $\sim 3000$  (NGC 6652) to more than 27000 (NGC 7078) stars have been identified in each cluster, from  $\sim 2$  magnitudes below the TO to the tip of the giant branch (GB). Such a large sample of stars is of particular importance to check the stellar

clock (Renzini & Fusi Pecci 1988), and a comparison with the theoretical luminosity functions (LF) is in progress.

All the evolved branches of the CMD are clearly identifiable in the 13 clusters. In particular, we note that all the 13 clusters show a well-defined blue straggler (BS) sequence, extending from the TO to about 2.5 magnitudes brighter. In only a couple of cases (NGC 6441 and NGC 6522) does the strong field contamination make it difficult to extract the true cluster BS population. A population of supra-HB stars is visible in at least 7 clusters: NGC 1851, 1904, 2808, 6388, 6441, 6522, and 7078.

The most exciting features in the present set of CMDs concern the HB. Six clusters (NGC 1904, 2808, 6388, 6441, 6552, 7078), plus probably also NGC 362, show extended blue HB tails. In all cases the blue tail seems to extend down to the photometric limit of our data. In particular, the HB of NGC 2808 is densely populated down to at least two magnitudes below the TO. There are at least two unexpected and, at the moment, inexplicable findings:

- the blue horizontal branches, with extended blue tails, in the two metal-rich clusters NGC 6388 ( $[\text{Fe}/\text{H}] = -0.60$ ) and NGC 6441 ( $[\text{Fe}/\text{H}] = -0.53$ );
- the clumpy nature of the extended blue HB tail of NGC 2808.

### 3.1. NGC 6388 and NGC 6441

A more detailed discussion of NGC 6388 and NGC 6441 will appear in Rich *et al.* (1997).

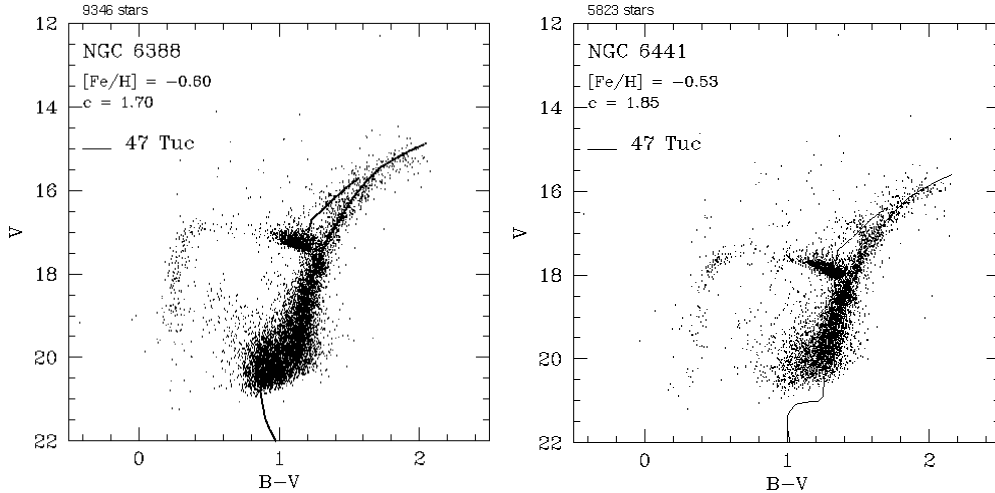


Figure 2. (left) The  $(B, B - V)$  CMD of NGC 6388 is compared with the fiducial sequence of 47 Tuc. The slopes of the giant branches of the two clusters are similar (the NGC 6388 giant branch is marginally flatter), suggesting similar metal content. (right) As in the left panel, but for NGC 6441. Again, the metallicity of NGC 6441 cannot differ much from that of 47 Tuc. The color extent of the red HBs of NGC 6388 and NGC 6441 is greater than that of the HB of 47 Tuc.

Regarding the average metal content of NGC 6388 and NGC 6441 there are very few doubts. Figure 2 reproduces their CMDs. For comparison, we have over-plotted the fiducial points of the CMD of 47 Tuc ( $[\text{Fe}/\text{H}] = -0.71$ ). This comparison clearly shows that the giant branches of NGC 6388 and NGC 6441 have similar slopes to that of—or are marginally flatter than—the giant branch of 47 Tuc. This means that, on average, they have the same—or slightly higher—metallicity than 47 Tuc. On the basis of their metal content we would expect to see only a red stub of the HB. Instead, we see also a

prolonged HB tail, which extends to the limit of our photometry in both of them, with a clear presence of at least one and possibly two gaps, which remind us of the gaps in NGC 2808. No standard evolutionary model can reproduce these blue tails and the red HB at the same time. We note here that in view of the presence of both the (unexpected) blue tail and of the red HB stub, NGC 6388 and NGC 6441 might be regarded as two further examples of clusters with a bimodal HB (like NGC 1851 and NGC 2808), or better, as the most metal rich among the known bimodal-HB GCs. Whatever the origin of the blue tail is, NGC 6388 and NGC 6441 tell us that a truly metal-rich old population can also create hot blue stars, and this result might be related to the ultraviolet flux increase towards shorter wavelengths discovered in elliptical galaxies (Bertola *et al.* 1980).

A close inspection of the CMDs in Figure 2 (*cf.* also Figure 1 in Sosin *et al.*) shows that the red HB is peculiar, as is in general the entire CMD. Indeed, we can compare the CMDs of NGC 6388 and NGC 6441 with the CMDs of the other metal-rich clusters in the present sample, i.e., 47 Tuc, NGC 5927, and NGC 6624. In these three clusters, the red HB (RHB) is very well defined, well confined to a restricted color interval, almost parallel to the color axis, and very well separated from the red GB (RGB). NGC 6388 and NGC 6441 have a completely different RHB, spread out in a larger color interval, inclined with respect to the color axis, merging with the RGB on the red side. These features might be thought to be due to differential reddening or to crowding effects. We are presently running artificial-star tests, but it is unlikely that internal photometric errors can be the explanation, as the effect is perfectly visible in a similar way also in the CMDs from the WF3 and WF4 chips alone, which are much less crowded. There might be some differential reddening, though the average reddening is not very high ( $< 0.4$  mag) and the covered field is very small, particularly with the PC camera, while the effect is visible in every single WFPC2 chip. A direct comparison of the CMDs in different regions of NGC 6388 shows that there is no average zero-point difference at scales larger than about 8 arcsec. So if there is some differential reddening, it must be present at scales smaller than 8 arcsec, still leaving the average reddening the same at large scales in the chip area of about  $160 \times 160$  arcsec<sup>2</sup>. On the contrary, there might be some differential reddening in NGC 6441, at the level of a few hundredths of a magnitude. Differential reddening might be a possibility, though it is does not seem likely, at least for NGC 6388.

There is another possibility, which might be an interesting working hypothesis. At a first glance, the CMDs of NGC 6388 and NGC 6441 strongly recall the CMD of  $\omega$  Cen, apart from the RHB, raising the suspicion that also in the former two clusters there might be some spread in metallicity. At least qualitatively, a spread in metallicity might be an appealing explanation for the anomalous HB and for the spread in the RGB. Of course, this is just a possibility, suggesting that it might be of some interest to study the metal content of a few single stars in these clusters.

Another working hypothesis is that there might be two stellar populations in the cluster, with two different ages. This possibility has been excluded for all the other known bimodal GCs, and it seems unlikely that it can work for NGC 6388 and NGC 6441. Unfortunately, the present material does not allow testing this hypothesis.

There is a further possible explanation for the BHB tail in NGC 6388 and NGC 6441: it might well be possible that their BHBs originate from the same phenomenon (whatever it is) of core dynamics that is responsible for the bluer and longer HB tails in the clusters with denser cores (Fusi Pecci *et al.* 1993, Buonanno *et al.* 1997). Again, NGC 6388 and NGC 6441 would be the most metal-rich clusters in which the phenomenon has been discovered. Tidal stripping of red-giant envelopes during close stellar encounters has been suggested as a possible cause (see, however, Djorgovski *et al.* 1991). Indeed, Rich *et al.* (1997) have calculated that NGC 6388 and NGC 6441 have among the highest

collision rates for any globular cluster in the Galaxy. It is therefore possible that these high collision rates are responsible for the extended BHB. But this scenario presents a problem: if tidal collisions are responsible for the production of the hot HB stars, we would expect them to have a different radial distribution compared to other evolved stars in the cluster. However, we find that blue and red HB stars, subgiants, red giants, and asymptotic GB stars all have the same radial distribution (in these and in all the other 11 clusters), and this might be a serious problem for the tidal-stripping model.

### 3.2. NGC 2808

A detailed discussion of the results on NGC 2808 will be presented by Sosin *et al.* (1997).

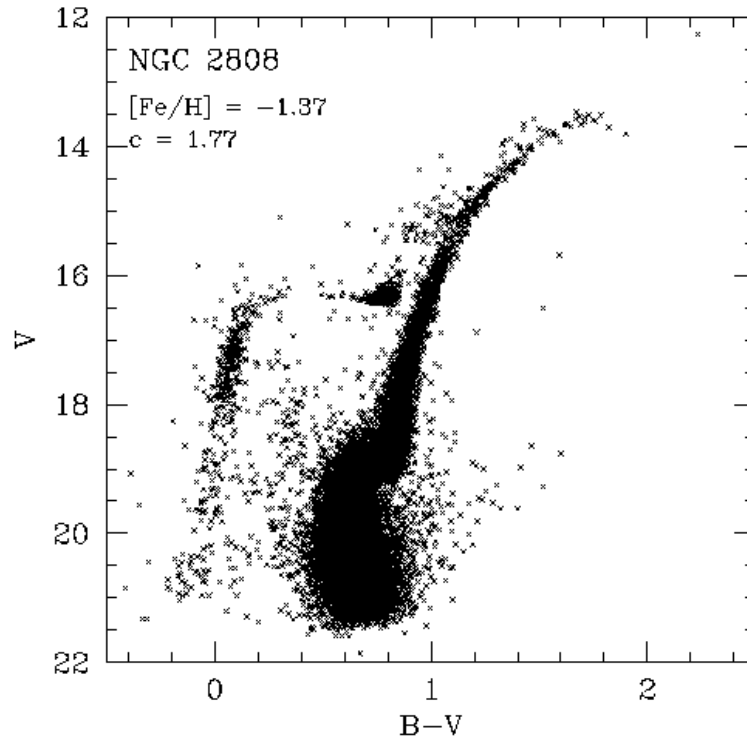


Figure 3. The  $V$  vs.  $(B - V)$  CMD for 27286 stars in NGC 2808. Note that the HB population is divided into four groups, separated by three gaps.

The  $(V, B - V)$  CMD of NGC 2808 is presented in Figure 3. This cluster was already known to have a bimodal HB with a blue and red HB more or less evenly populated. What is new here is that the long blue tail of the HB extends down to  $V = 21$ , at the limit of our photometry. The blue tail is not evenly populated: there are two significant gaps (*cf.* also Figure 2 of Sosin *et al.*, in the following paper) at  $V = 18$  and at  $V = 20$  and colors  $F218W - B = -1.3$  and  $-2.0^\dagger$ , corresponding to effective temperatures  $\log T_{\text{eff}} = 4.23$  and  $4.40$ , respectively. As shown in Sosin *et al.* (1997), the two gaps in the blue tail correspond to masses near  $0.54$  and  $0.495 m_\odot$ , and the widths of the depleted regions in mass are very narrow,  $\sim 0.01 m_\odot$ . To these two gaps we have to add also a third gap,

<sup>†</sup> Note that while the F439W and F555W magnitudes have been converted to Johnson  $B$  and  $V$  magnitudes, the F218W magnitudes have been calibrated to the STMAG instrumental system, using the zero points in the tables of Holtzman *et al.* (1995).

between the red and blue HB. As far as the discontinuities in the HB distribution are concerned, NGC 2808 is not unique. If we look at the 13 CMDs in the present paper, we will see gaps which recall the gaps in the blue tail of NGC 2808 (but are not necessarily similar or of similar origin) also in NGC 1904, NGC 6441, NGC 7078, and perhaps NGC 6388. Moreover, two significant gaps at more or less the same temperature as the gaps in NGC 2808 are also present in the blue HB of high-latitude halo subdwarfs (Newell 1973). So gaps might be not an exceptional feature in the blue HB.

It is not clear what the origin of these gaps is. In any case, either the BHB stars have a particular set of properties which make them land in well-defined regions of the HB after the helium flash, or the stars which happen to fall on the gap regions rapidly evolve off them. While this last possibility might (at least partially) explain the intermediate gap (close to the mass where the HB evolution changes from predominantly redward to blueward), no obvious reason can be found for the other two gaps (*cf.* Sosin *et al.* 1997).

As in the case of NGC 6388 and NGC 6441, at the moment we have no satisfactory explanation for the multi-modality of the HB of NGC 2808. It might be due to dynamical effects, mass-loss processes, or a combination of factors. For sure, the peculiar HBs of these clusters strongly remind us how poor is our knowledge of the mass-loss processes, which are the main cause of the HB morphology, as they set the final stellar envelope mass, i.e., where the stars should move after the helium flash.

#### 4. The blue stragglers

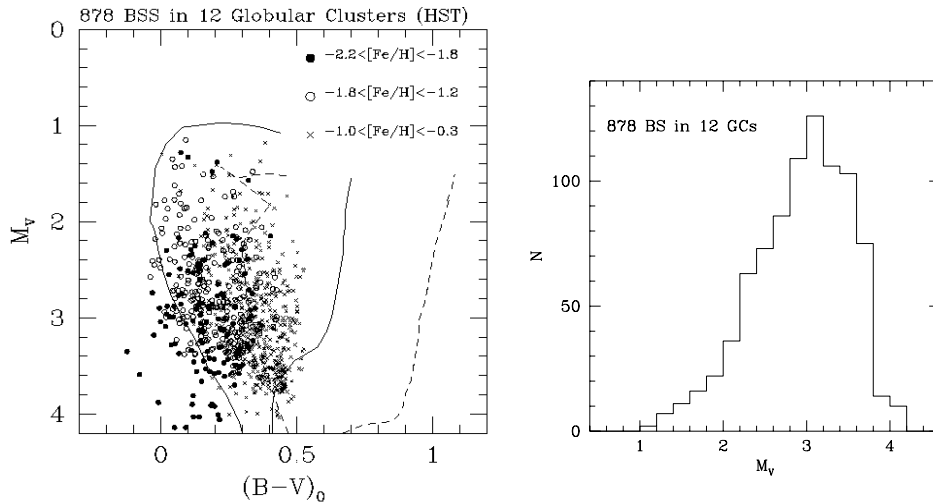


Figure 4. The *left panel* shows The  $M_V$ ,  $(B-V)_0$  CMD for the 878 BSs selected from 12 clusters in our sample. The BSs have been divided into 3 metallicity groups. The isochrones for a  $1.6 m_\odot$  and a  $0.8 m_\odot$  star with metallicities  $Z = 10^{-4}$  and  $4 \times 10^{-3}$  are also plotted. The *right panel* shows the  $V$  luminosity function for the same BSs.

As already noticed in the previous Sections, all of the 13 clusters in the present sample have a population of blue stragglers. We will discuss the properties of the BSs in a forthcoming paper (Piotto *et al.* 1997).

Here we want to present only a few preliminary results. A sample of 878 BSs have been extracted from 12 of the 13 clusters in our sample (even though NGC 6522 appears to have a BS population, the contamination by field stars prevented us from extracting

its BSs). This is the largest sample of BSs in GCs available so far (*cf.* Fusi Pecci *et al.* 1993 for a comparison). Moreover, all the BS magnitudes are in a single, photometrically homogeneous system.

Figure 4, *left panel*, shows the  $M_V, (B-V)_0$  CMD for the 878 BSs. Distance moduli and reddenings have been extracted from the compilation by Djorgovski (1993). The BSs of Figure 4 have been divided into three metallicity groups (see labels). As expected, the BSs become bluer and bluer as the metallicity decreases. In the same figure we have plotted the isochrones (from Bertelli *et al.* 1994) for a  $1.6 m_\odot$  star for the two metallicities approximately corresponding to the extreme metallicities of our sample of GCs (the full line is for  $Z = 10^{-4}$  and the dashed line is for  $Z = 4 \times 10^{-3}$ , respectively). On the red side are the isochrones for a  $0.8 m_\odot$  star for the same metallicities. The *right panel* of Figure 4 shows the LF from the 878 BSs.

Here we briefly summarize the main results on the BS population:

- The brightest BSs have magnitudes as bright as, but not exceeding the magnitude of the most metal-poor isochrone for a  $1.6 m_\odot$  star. In other words, the masses of the BSs in our sample do not exceed twice the mass of a normal TO star (note that their masses could be smaller, according to the BS evolutionary models by Baylin & Pinsonneault 1995).
- There are many BSs redder than the  $Z = 4 \times 10^{-3}$  isochrone. This might be due both to photometric errors and to the evolution of these stars off the main sequence.
- It might be harder to explain the presence of a group of metal-poor BSs significantly bluer than the  $Z = 10^{-4}$  isochrones. We need to run artificial-star experiments, but it seems unlikely that all those objects come from photometric errors.
- In all the 12 clusters, a Kolmogorov–Smirnov test has shown that the BSs are more concentrated than the subgiants of the same magnitudes, with a confidence level that is always greater than 99.99%. This result is of particular interest because this is the only group of stars whose radial distribution differs significantly from the others.
- The BSs closer to the center are marginally bluer and significantly brighter than the BSs farther from the center.
- The LF shows that there are BSs up to 3 magnitudes brighter than their corresponding TO. The LF rises steeply up to  $M_V \sim 3.1$ , while the significance of the apparent decline at fainter magnitude is uncertain, due to the possible bias in selecting the BSs. No significant gaps can be found in the present LF.

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